External Grant Award Nos. 07HQGR0050, 07HQGR0038, 07HQGR0045, and 07HQGR0047

DEVELOPMENT OF A CALIFORNIA-WIDE THREE-DIMENSIONAL SEISMIC WAVESPEED MODEL: COLLABORATIVE RESEARCH WITH UW-MADISON, LDEO/COLUMBIA UNIV., U. C. SAN DIEGO, AND CALTECH

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Abstract

We present a preliminary statewide, three-dimensional (3D) tomographic model of the P-wave velocity structure of the crust and uppermost mantle of California. The dataset combines first arrival times from earthquakes and identified quarry blasts recorded on regional network stations, and travel times of first arrivals from explosions and airguns recorded on profile receivers and network stations. The model presented here is obtained by using a regional-scale double-difference tomography algorithm, which incorporates a finite-difference travel time calculator and spatial smoothing constraints. This algorithm is designed to solve jointly for 3D velocity structure and earthquake locations using both first arrival times and differential times, leading to improved resolution in the seismically active areas where the differential data provide dense sampling. Our preliminary model is coarse (uniform 30 km in horizontal and variable vertical gridding) but is able to image the principal features present in previous separate regional models for northern and southern California, such as the high-velocity subducting Gorda Plate, upper-crustal velocity highs beneath the Sierra Nevada and much of the Coast Ranges, low velocities of the Great Valley, Ventura Basin, Los Angeles Basin, and Imperial Valley, and a high-velocity body in the middle to lower crust underlying the Great Valley. The new statewide model has improved areal coverage compared to previous models, and also extends to greater depth due to the inclusion of substantial data at large epicentral distances. This model can be applied to a variety of regional-scale studies in California, such as providing a preliminary unified statewide earthquake location catalog and regional waveform modeling.

Project Results

We report on our progress in the development of the first statewide three-dimensional (3D) seismic velocity model for California. The collaborative project involves four university institutions, UW-Madison, LDEO/Columbia Univ., U. C. San Diego, and Caltech, and is coordinated with USGS internal projects. This year, the PI team carried out the following tasks: (1) merging of existing earthquake arrival time datasets and data compilation for controlled-source profiles; (2) quality-control analysis of the merged dataset; (3) software development for regional-scale tomography; (4) preliminary compilation of prior information and constraints on velocities and Moho depths; (5) construction of a preliminary 3D crustal model.

Previously, the largest and most complete crustal tomography models in California were the southern California model of Lin et al. (2007) and the northern California model of Thurber et al. (2008). Our California statewide velocity model represents an extension of these previous models with more complete data coverage, and will ultimately provide the basis for regional-scale earthquake location and waveform modeling and other studies.

One of the key tasks this year has been tomography software development. One of the major achievements is incorporation of a practical and effective matrix decomposition algorithm, known as BPRO (Bidiagonalization with Partial Re-Orthogonalization (Larsen,1998)), into the original double-difference algorithm tomoDD (Zhang and Thurber, 2003) for model resolution and covariance matrix estimation for this huge inverse problem (Zhang and Thurber, 2007). This capability will next be incorporated into the regional-scale version of tomoDD. Another accomplishment is the testing, validation, and hybridization of a spherical-Earth finite-difference travel-time code, in collaboration with S. Roecker. The hybridization involves using the ray paths derived from the finite difference solution as starting paths for a spherical pseudo-bending ray tracing algorithm based on Sekine and Koketsu (1998). Starting with the finite-difference method helps avoid potential problems with local travel time minima, and finishing with pseudo-bending results in a significantly improved path, according to our synthetic tests. Thus, the hybrid scheme is efficient and extremely accurate. A third accomplishment is the incorporation of adaptive-mesh capability (Zhang and Thurber, 2005) into the regional-scale DD tomography code (Zhang et al., 2004, 2006). This adaptive code is the key to the final phase of tomographic modeling in Year 2 of the project, as described below.

Our data sets for this preliminary model are the first-arriving P times for natural earthquakes, including 4331 events in northern California (shown by the light-blue dots in Figure 1) recorded by the Northern California Seismic Network from Thurber et al. (2008), 739 events in central California (shown by the green dots in Figure 1) recorded by the PG&E network from Hardebeck (pers. comm., 2007), and 2451 "composite events" in southern California (shown by the pink dots in Figure 1) from Lin et al. (2007). A major contribution of our statewide model development is the identification of earthquakes yielding arrival times at both the Northern and Southern California Seismic Networks. These events are critical to the determination of the seismic velocity model in central California, in the former "no-mans-land" between the northern and southern California networks.

In order to constrain the shallow crustal structure and absolute locations, we assembled travel times of first arrivals from 3110 explosions and airguns (the red open circles in Figure 1) recorded on profile receivers and network stations. The principal active-source datasets are listed in Table 1. Quarry blasts, which have known locations but unknown origin times, are valuable to include in tomographic inversions because they help improve the spatial coverage. We include data from 44 quarry blasts (the blue open circles in Figure 1), with 19 in southern California (Lin et al., 2007) and 25 in northern California.

The horizontal nodes in our model are uniformly spaced at 30 km intervals and extend 540 km in the SE-NW direction and 1320 km in the SW-NE direction (Figure 1). The vertical nodes are positioned at -1, 1, 4, 8, 14, 20, 27, 35 and 45 km (relative to mean sea level). Preliminary inversions were carried out using the tomography algorithm simul2000 (Thurber and Eberhart-Phillips, 1999). This algorithm simultaneously solves for 3D velocity structure and earthquake locations using the first arrival times employing an iterative damped-least-squares method. This step was taken for data quality control purposes (i.e., identifying poorly constrained events and picks with very high residuals) and to provide a formal but approximate estimate of velocity model resolution and uncertainty. The model presented here is obtained by using a regional-scale double-difference tomography algorithm (Zhang and Thurber, 2006), which incorporates a finite-difference travel time calculator and spatial smoothing constraints. This algorithm is designed to jointly solve for 3D velocity structure and earthquake locations using both first arrival times and differential times, leading to improved resolution in the seismically active areas where the differential data provide dense sampling. Only absolute times were used in determining this preliminary statewide model due to computational limitations. Differential times from both the catalog picks and waveform cross-correlation will be used for the next phase of inversions. The smoothing constraint weighting in the horizontal and vertical directions (20) and the damping parameter (300) were chosen by examining the data variance versus model variance trade-off curves. The root mean square (RMS) arrival-time residuals were reduced from an initial value of 1.45 s to 0.38 s.

Figure 2 shows selected map view slices of the resulting tomographic model. Although our current model is coarse, it is able to image the principal features present in previous separate regional models for northern and southern California. Figure 2a shows the P velocities in the 1 km depth slice. The average velocity value in this layer is 4.83 km/s. The white contours enclose the areas where the derivative weight sum (DWS) is greater than 300, which are similar to 0.3 resolution contours directly estimated from the simul2000 algorithm of Thurber and Eberhart-Phillips (1999). The velocities generally correlate with the surface structures. Lower values are observed in basin and valley areas, such as the Great Valley, Ventura Basin, Los Angeles Basin, Southern San Joaquin Valley and Imperial Valley, whereas relatively higher velocities are present in the mountain ranges, such as the Sierra Nevada, Transverse Ranges and Peninsular Ranges. Near-surface velocities are also relatively high in the Mojave Desert.

Velocities at mid-crustal depth (14.0 km) are shown in Figure 2b. Although velocity variations appear subdued compared to Figure 2a, most of this layer is well resolved. Some of the features we see at 1.0 km depth are reversed at this depth, e.g., the basin and valley areas show relatively high velocity anomalies and lower values are present under the mountain ranges.

The quality of our model can be evaluated by its ability to (a) fit the observed arrival time data and (b) produce accurate locations for on-land controlled-source explosions, which have coordinates that are known. Figure 3 shows a comparison of the earthquake arrival time residual distribution (top) before and (bottom) after 3D velocity inversion. The root-mean-square misfit is reduced by over a factor of 2, from 0.79 s to 0.38 s. Figure 4 shows histograms of shot location accuracy in the starting 1D model compared to the 3D model for both vertical and horizontal coordinates. For the 1D model, the error distributions are quite broad, with a peak in the horizontal error distribution at about 2 km, a mean error of 2.3 km, and a standard deviation of 1.9 km. The 1D vertical error distribution is bimodal with peaks at about 0 and 6 km, a mean error of 4.8 km, and a standard deviation of 4.0 km. In contrast, the 3D model error distributions are sharply peaked between 0 and 1 km, with mean errors of 0.8 and 0.3 km and standard deviations of 0.8 and 0.8 km for the horizontal and vertical errors, respectively.

Our next step is to densify the model grid and include the millions of differential times from both catalog picks and waveform cross-correlation to improve the model resolution, especially in the seismically active areas. In order to accomplish this orders-of-magnitude increase in data and grid nodes on available computer platforms, we will subdivide the region and solve for a fine model in a given sub-region while retaining a coarser model in the rest of the state. Figure 5 shows the sub-region grids we plan to use in this final stage of modeling. The overlapping subregion models will be merged to produce the final statewide model.

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Table 1. Active-source datasets included in the statewide tomographic inversion.

Experiment Name	Year	No. Shots	No. Stations
Southern Sierra	1993	23	1241
LARSE 1999	1999	78	925
Imperial Valley	1979	41	932
PACE 1992	1992	5	384
Western Majove Desert	1980	10	245
Morro Bay	1982	9	230
San Luis Obispo	1986	10	123
Coalinga	1983	9	209
LARSE 1994	1994	125	889
Great Valley	1981/1982	7	221
Shasta 1981	1981	1	274
Shasta 1982	1982	9	299
Geysers-San Pablo Bay	1976	5	135
Gilroy-Coyote Lake	1980/1981	4	236
Livermore	1980/1981	3	251
Loma Prieta	1990	2252	16
Long Valley	1983	9	278
Oroville	1977	5	118
San Francisco Bay 1991	1991	6	300
San Francisco Bay 1993	1993	14	399
San Juan Bautista	1981/1982	6	335
USGS	1967	9	147
Parkfield	2003	157	242
Network, 1976-2003	270	659	

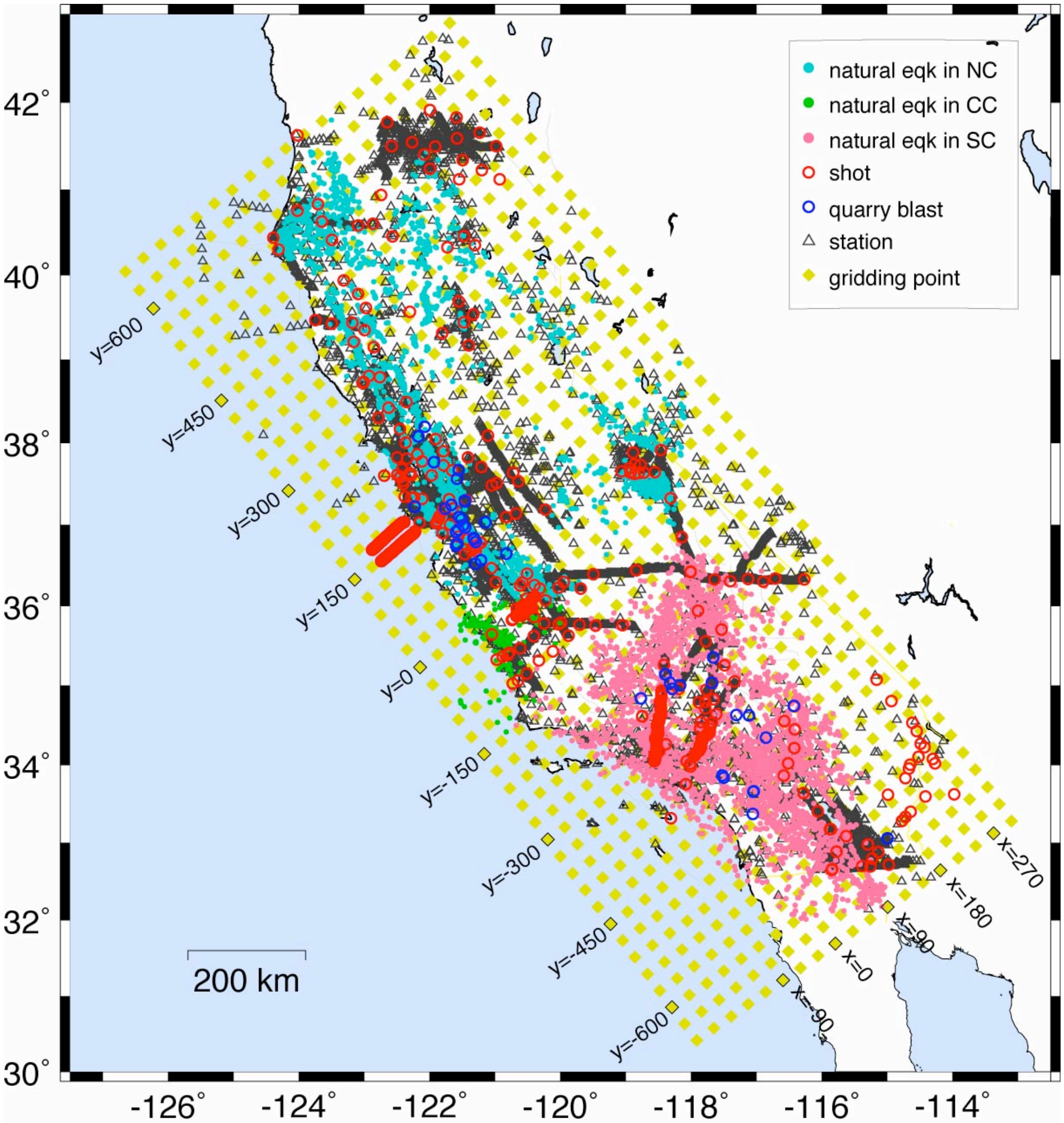

Figure 1. Event and station distributions in our study and the 30-km grid spacing of our model.

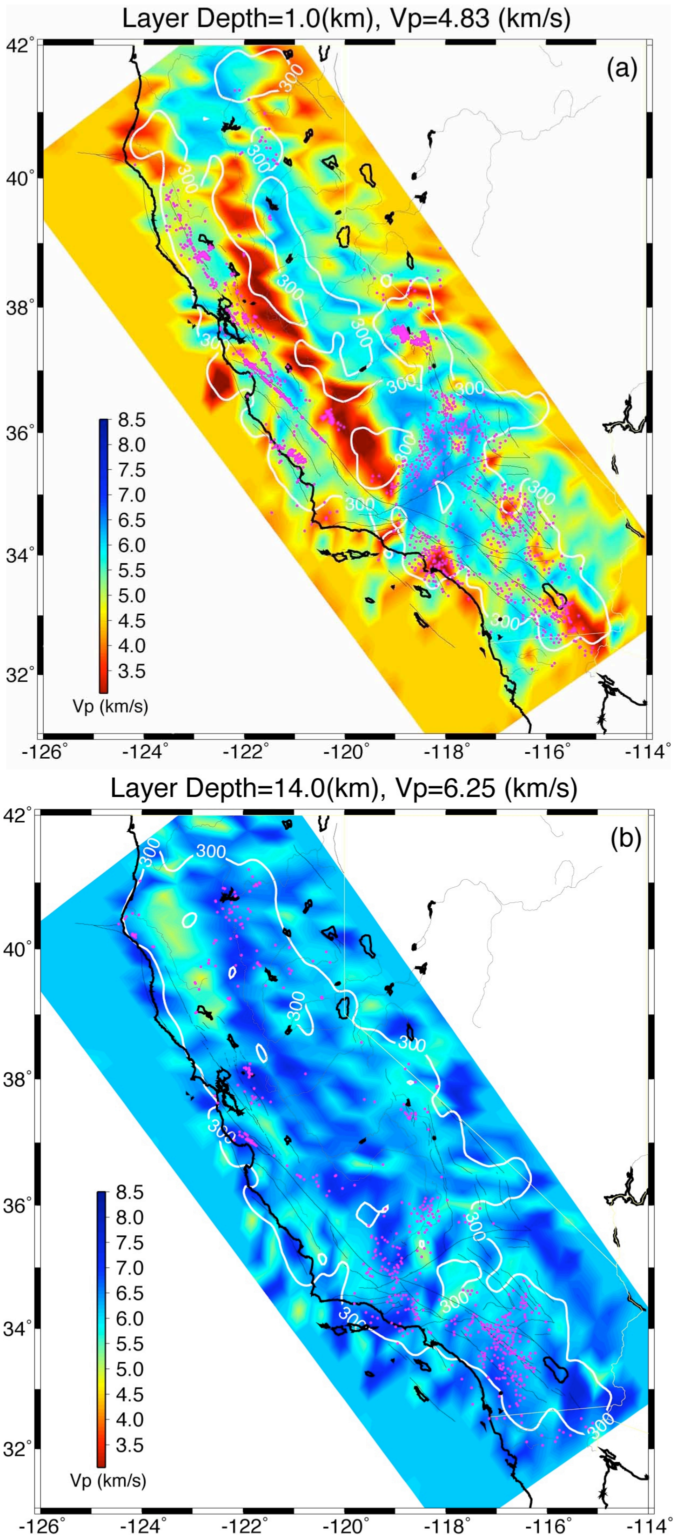

Figure 2. Map views of the absolute P velocity at 1 and 14 km depths. The white contours enclose the areas where the derivative weight sums (DWS, an approximate measure of resolution) is greater than 300.

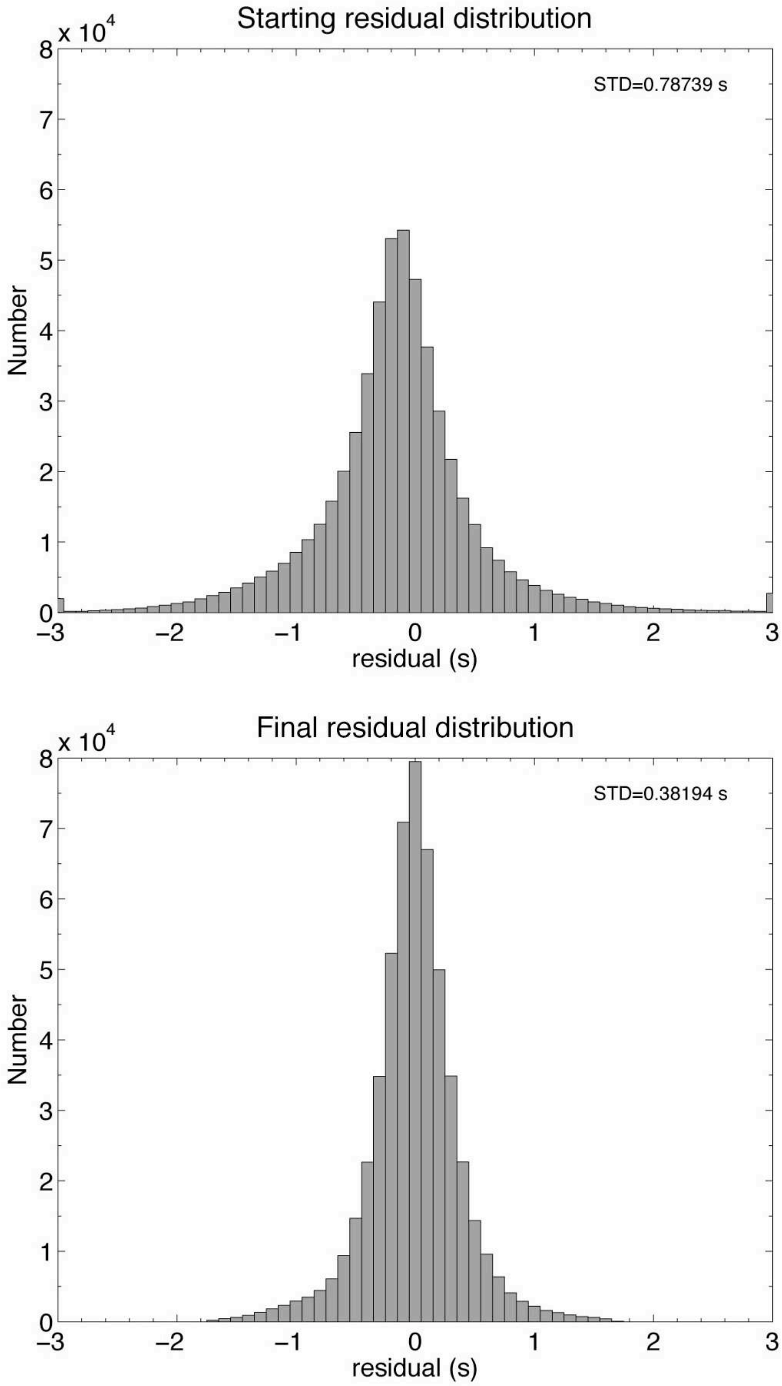

Figure 3. Comparison of arrival time residual distribution (top) before and (bottom) after 3D velocity inversion. Root-mean-square misfit (STD) is reduced by over a factor of 2.

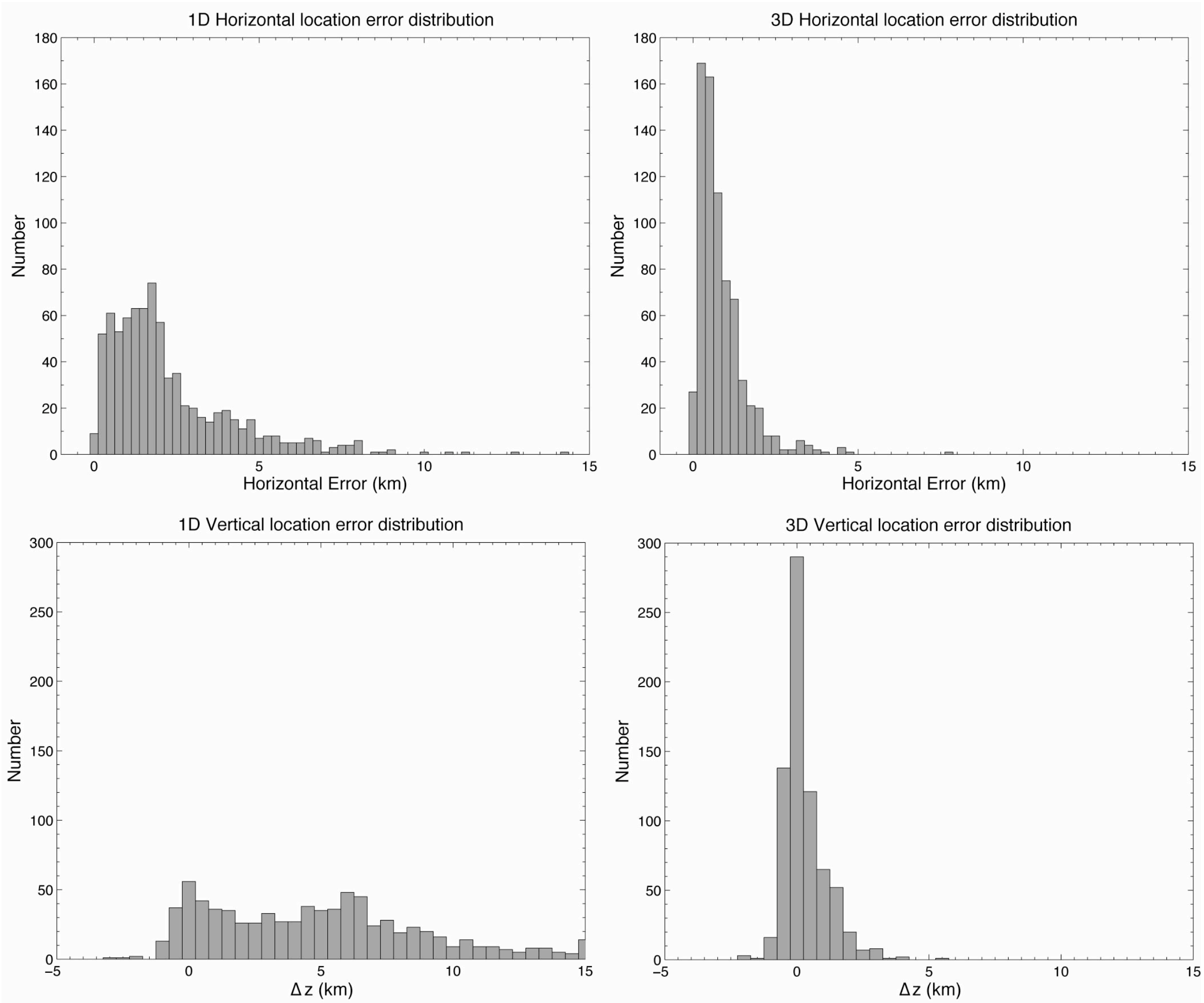

Figure 4. Comparison of the accuracy of shot relocation in the starting 1D model versus the final 3D model. Top: (left) 1D and (right) 3D horizontal location errors. Bottom: (left) 1D and (right) 3D vertical location errors.

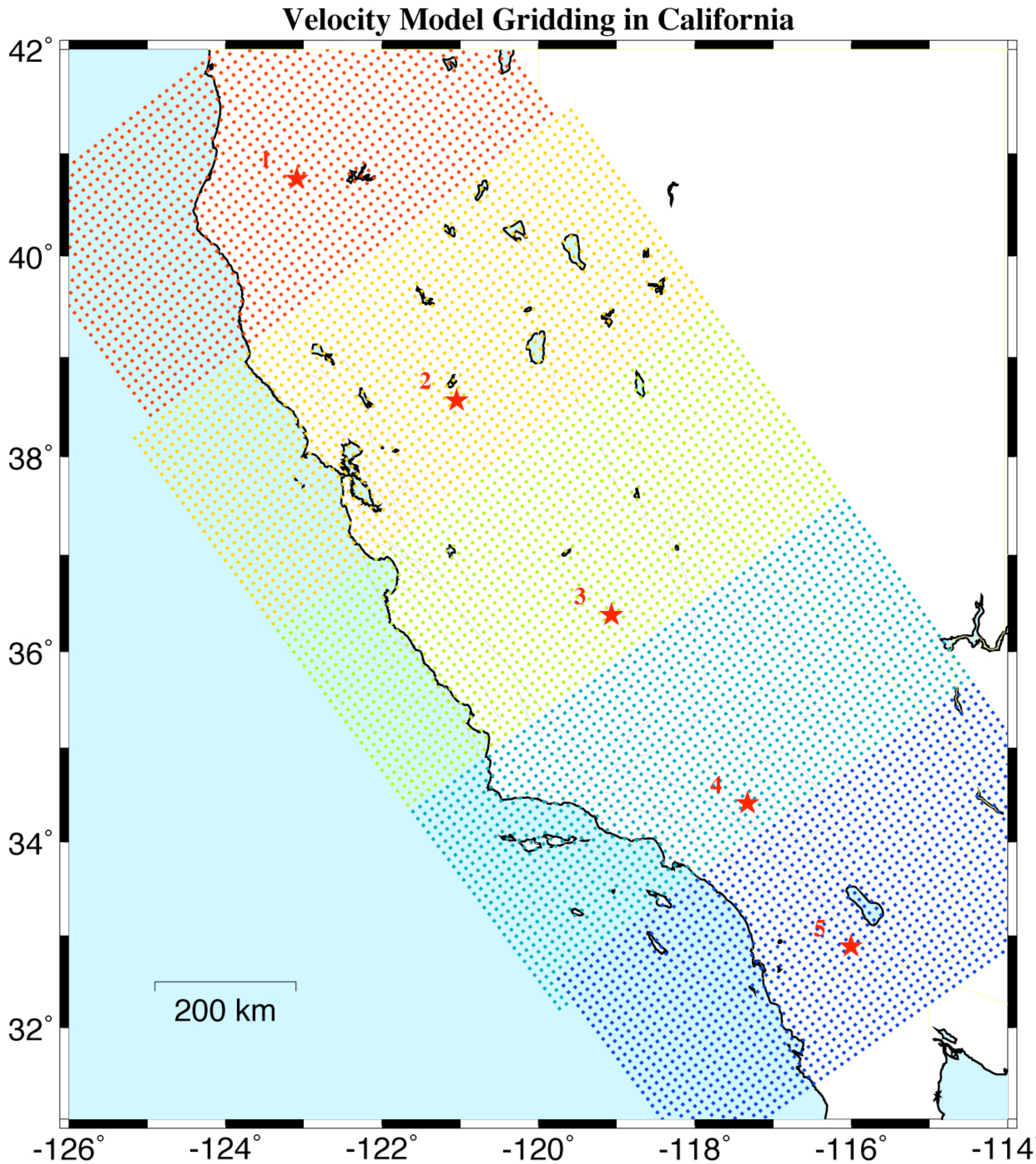

Figure 5. Sub-region grids to be employed in the final stage of tomographic modeling. Note that the five grids will overlap to allow for averaging and smoothing between models to arrive at the final statewide model.